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Experimental Investigation of the Effects of Various Plasma Actuator Configurations on Lift and Drag Coefficients of a Circular Cylinder Including the Effects of Electrodes

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Abstract

In this paper, the effects of the existence of plasma actuator electrodes and also various configurations of the actuator for controlling the flow field around a circular cylinder are experimentally investigated. The cylinder is made of PVC (Polyvinyl Chloride) and considered as a dielectric barrier. Two electrodes are flush-mounted on the surface of the cylinder and are connected to a DC high voltage power supply for generation of electrical discharge. Pressure distribution results show that the existence of the electrodes and also the plasma are able to change the pressure distribution around the cylinder and consequently the lift and drag coefficients. It is found that the effect of the existence of the electrodes is comparable with the effect of plasma actuator in controlling the flow field around the cylinder and this effect is not reported by other researchers. Eventually it is concluded that the existence of the electrodes or any extra objects on the cylinder and also the existence of the plasma are capable of changing the flow field structure around the cylinder so that the behavior of the lift and drag coefficients of the cylinder will be changed significantly.

Keywords: plasma actuator; DC high voltage power supply; generalized glow regime; flow control; wind tunnel

1. Introduction

Controlling the flow field around bodies such as cylinders, airfoils, flat plates, compressor and turbine cascades, etc. is of interest in aerodynamics because by controlling the flow field properly, we can modify the flow field structure so that the aerodynamic characteristics of the body would be improved. There are two kinds of methods for controlling the flow field including: a) passive flow control methods; b) active flow control methods. In passive flow control methods, energy as an input for the system is not needed. Some examples of this kind of flow control methods are boundary layer trips, roughness elements, ejector nozzles and surface perturbations. It is important to mention that these kinds of flow control methods are only useful for low Reynolds number flows because at high Reynolds number, they would increase the drag coefficient significantly. In active flow control methods, the input energy of the system can be in forms of heat, laser, electron beams, micro waves, acoustic energy, plasma, etc. Some examples of these methods are surface blowing to contrast a pseudo streamlined-shaped surface, surface suction to obtain a thinner boundary

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layer, oscillations of the body, synthetic jets. These flow control methods are more flexible in comparison with the passive ones because the energy in the input of the system can be turned on and off as needed. The main goal of active flow control methods is to reattach the separated flow to the surface and this method has been applied by many researchers during recent years [1-3].

One of the useful instruments for controlling the flow field actively is plasma actuator. During recent years, too much attention has been paid to plasma actuators for this purpose [4-5]. They consist of two electrodes which are separated by a dielectric material such as plastic, quartz, nylon, teflon, and kapton, etc. When the electrodes are connected to the positive and negative polarity of a DC high voltage power supply, positive ions and negative ions (electrons) would be generated at anode and cathode respectively. As the voltage difference between the electrodes increases, electrical field would become more intensive and eventually Columbian force would be generated. This force causes the positive ions attractive to the negative ones and vice versa and while they are migrating, they would collide to neutral particles and exchange their momentum with them. Therefore it can be claimed that the principle of plasma actuators is based on momentum transfer. As a result, an ionized fluid flow comprises of positive and negative ions (electrons) is produced which is directed from anode to cathode because the mass of the electrons is negligible in contrast to the positive ions. This ionized flow is called ionic wind (plasma) and produces a tangential wall jet at close vicinity of the cylinder surface which modifies the flow structure around the circular cylinder. Plasma actuators have many advantages such as simplicity, reliability, no moving part, low cost and weight, quick response time, easily installation. On the other hand, the main disadvantage of plasma actuators is the generation of ozone gas during their operation which is harmful for human's health. Since the plasma actuators have considerable advantages, they have been successfully used in a variety of different flow control applications including exciting boundary layer instabilities on a sharp cone at Mach 3.5 [6], lift augmentation on a wing section [7], low pressure turbine blade separation control [8], turbine tip clearance flow control [9], bluff body control [10], drag reduction [11], unsteady vortex generation [12] and airfoil leading edge separation control [13]. The main concentration of this paper is to control the flow field around a circular cylinder, so a summary of experiments which have been done by previous researchers in this matter will be mentioned with detail.

Artana, et al. [14] controlled the near-wake region around a circular cylinder by using plasma actuators for Reynolds number Re from 2 300 up to 58 000. The plasma actuator for this purpose consisted of a wire electrode (copper wire) and a planar electrode (an aluminum foil) which were located at stagnation point and θ=180° (θ is the angular location of the planar electrode according to the wire electrode, that is the stagnation point) respectively. They concluded that plasma actuators modified the size of the mean recirculation region and produced an increase in the shear stresses of the layers bounding the contour of this region. In addition to the control of the near-wake region, they calculated the pressure distribution around the circular cylinder at Re = 21 600 and 57 600 when the plasma actuator was on and off. The pressure distribution results showed that the plasma actuators played no important role in separation point and they decreased the pressure coefficient more as Reynolds number increased. McLaughlin, et al. [15] applied dielectric barrier discharge (DBD) plasma actuator to a circular cylinder at Reynolds number of 7 400 to control the cylinder wake vortex. Preliminary data indicated that plasma actuators were effective in controlling vortex shedding frequency and in achieving spanwise coherent shedding. They could also alter the vortex shedding frequency within forcing amplitude/frequency bands at lower Reynolds number. Flow visualization test showed that the actuators played a significant role in affecting the flow separation and the wake behavior. McMullin and Snyder [16] numerically studied the wakes control downstream of a cylinder. They applied a moving wall boundary condition to conduct simulations of the circular cylinder wake flow control at Re = 8 000. Large eddy simulation (LES) was able to predict the "lock-in" behavior and the spanwise coherence of the wake was quantified using a statistical correlation. A frequency analysis at a monitoring point in the wake showed the weak frequency peaks at harmonics of the forcing frequency. These peaks were apparently caused by additional small vortices induced by the instantaneous start/stop of the actuators. Finally McMullin and Snyder [16] concluded that the amplitude of the lift and drag oscillations is significantly increased by the actuators but that the mean drag may increase or decrease depending on the forcing frequency. Thomas, et al. [17] used several plasma actuators on a circular cylinder in order to decrease noise and Karman shedding at Reynolds number of 33 000. They performed steady and unsteady actuation for this goal and concluded that by either steady or unsteady actuation, Karman shedding was totally eliminated, turbulence levels in the wake significantly decreased and near-field sound pressure levels associated with shedding were reduced by 13.3 dB. Sosa, et al. [18] reduced the drag coefficient of a circular cylinder up to 25% by means of several electrode plasma actuators. They concluded that the DBD actuator, for a fixed value of the power coefficient added a higher momentum to the flow and consequently produced a higher drag reduction than the DBD actuator with the same power coefficient.

In this paper we are going to continue the research of Ref. [14] by studying experimentally the effects of the existence of the electrodes and also the plasma on the pressure distribution of the cylinder at various plasma actuator configurations. We have used two electrodes (a wire electrode and a planar one) like

Ref. [14]. For the initial configuration, the wire electrode was located at the stagnation point whereas the planar one was located at θ=180°. The other configurations were attained by rotating the cylinder at various angles in clockwise direction. Pressure distribution experiments were carried out for each configuration at Reynolds number of 63 825 (freestream velocity u = 37 m/s) when the plasma actuator was on and off and the lift and drag coefficients of the cylinder were calculated according to the pressure distribution results.

2. Experimental Setup

2.1. Wind tunnel

All the experiments of this study have been done in an open-loop low speed wind tunnel of rectangular cross section (0.3 m × 0.3 m) which is 60 cm in length that enables testing at flow velocities up to 40 m/s. The turbulence intensity of this wind tunnel is approximately 1%.

2.2. Model

A hollow cylinder with a 3 mm thick wall which is made of PVC (Polyvinyl Chloride) has been used for this study. The dimensions of this model are 300 mm in length and 30 mm in external diameter. Two electrodes have been used for producing electrical discharge. The electrodes are flush-mounted on the surface of the PVC cylinder. The electrodes consist of a wire electrode and a planar one. The wire electrode is a copper wire which is 0.9 mm in diameter and 250 mm in length. The planar electrode is an aluminum foil which is 200 mm long and 26 mm wide. The thickness of this foil is 50 μm and the gap between electrodes is 34 mm. The thickness of the planar electrode and also the diameter of the wire electrode are the same as those of Ref. [14]. Opposed to Ref. [14], a slit with full span of 300 mm, width and depth of 1 mm was contrived on the cylinder and the wire electrode was inserted into it. Furthermore the planar electrode was located in front of the wire one. Different configurations of plasma actuators have been investigated in this research. The initial configuration refers to when the wire electrode is at stagnation point and also the angle of that is 0° according to the horizon. Besides, the planar electrode locates at θ=180°. The other configurations of plasma actuators were achieved by rotating the cylinder in clockwise direction by 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165° and 180° respectively. Figure 1 shows the schematic of all configurations of plasma actuator. As is clear, the concentration of electrical charges is at sharp point like the corners of our planar electrode. In order to avoid this problem, the corners of the aluminum foil were rounded completely.

2.3. DC high voltage power supply

In order to apply a voltage difference high enough to sustain a stable electrical discharge, a DC high voltage power supply (50 kV, 20 mA) has been used. The wire electrode was connected to the positive polarity and the planar electrode was grounded. By increasing the voltage difference between both electrodes, we can reach the generalized glow regime. The characteristics of this regime will be mentioned later. A 2.5 MΩ resistor has been used in order to increase the security of the DC high voltage power supply system against electrical arcs because they carry high electrical currents and can damage the power supply system easily if preliminary cautions are not considered.

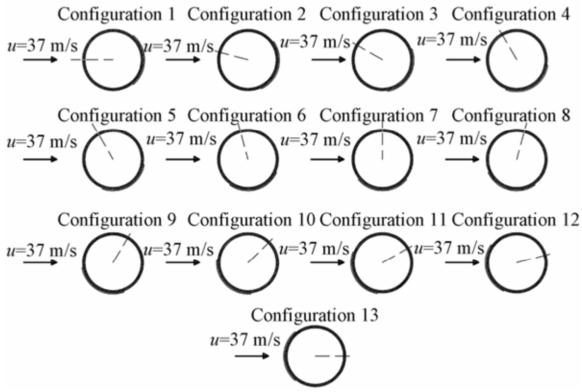

Fig. 1 Schematic of different configurations of plasma actuator.

2.4. Pressure measurements

In order to measure the pressure distribution around the circular cylinder, 18 pressure tapping holes have been mounted on the cylinder and were connected to a pressure transducer system. The diameter of these pressure tapping holes is 1.5 mm. The freestream velocity u was measured by a pitot static tube positioned at 13 cm upstream of the cylinder.

3. Results and Discussions

3.1. Generalized glow regime

When the plasma actuator was on, all of the experiments were carried out at generalized glow regime. The pattern of this regime shown in Figs. 2-3 is obtained by darkening the laboratory. This regime was characterized by a homogeneous luminescence covering the cylinder surface. The luminescence occupied the whole inter-electrode region and made the cylinder look like that it supported a thin film of ionized air (plasma). By visual inspection it seemed that the thickness of the ionized sheet was of the order of the thickness of the aluminum foil (50 μm). The corona discharge was homogeneous, showing a little bit noise and the current remained stable over a long period of time.

For each configuration of plasma actuators, the generalized glow regime established at a specific electrical current and voltage difference range. Table 1 shows the mean voltage difference and electrical current that the generalized glow regime was produced.

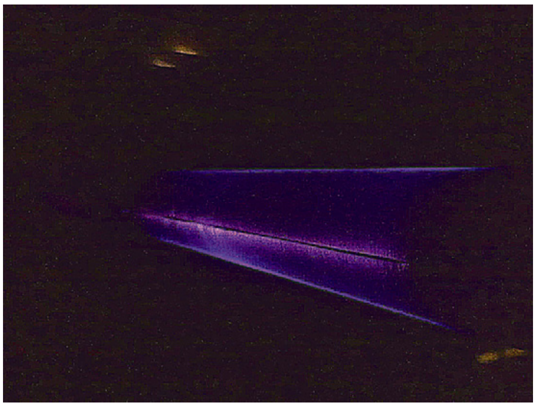

Fig. 2 Generalized glow regime (frontal view).

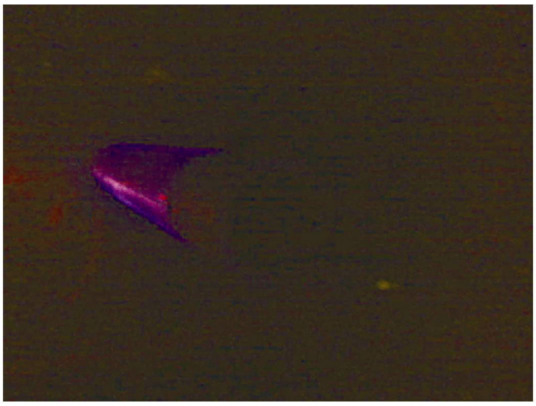

Fig. 3 Generalized glow regime (side view).

Table 1 Mean voltage difference and electrical current in generalized glow regime

Configuration	Angle of wire electrode/(°)	Mean voltage difference/kV	Mean electrical current/mA
1	0	23.55	0.550
2	15	23.85	0.500
3	30	23.80	0.400
4	45	23.90	0.375
5	60	24.00	0.350
6	75	24.00	0.300
7	90	24.25	0.300
8	105	24.50	0.250
9	120	24.60	0.200
10	135	24.75	0.200
11	150	24.70	0.200
12	165	24.70	0.200
13	180	25.35	0.200

The values of the voltage difference and the electrical current show that by increasing the angle of wire electrode (the angle of slit), higher voltage difference and lower electrical current are needed to sustain the generalized glow regime because as the angle of wire electrode increases, the momentum of the flow is not able to move properly the positive ions gathering at anode toward cathode. So in this case the electrical current decreases because the electrical current is due to the movement of the ions. On the other hand the total electrical power of DC high voltage power supply is constant. Therefore when the electrical current decreases, the amount of the voltage difference must be increased so that the electrical power remains constant. The mean voltage difference and the mean electrical current in term of the slit angle have been shown in Figs. 4-5.

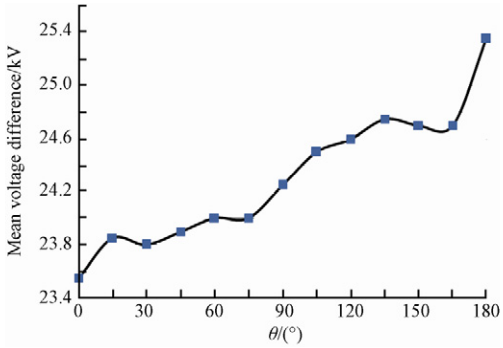

Fig. 4 Mean voltage difference.

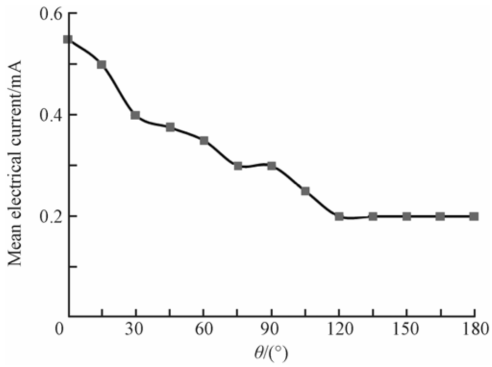

Fig. 5 Mean electrical current.

3.2. Effect of electrodes on pressure coefficient distribution of the cylinder

One of the most important matters that has not been considered in the previous researches is the existence of the electrodes on the cylinder and their effects on producing disturbance in the flow around the cylinder. When plasma actuators are off, electrodes on the cylinder can change the pressure coefficient C_p distribution over the cylinder and also the behavior of the lift and drag coefficients significantly. For instance, Fig. 6 shows the pressure coefficient distribution of a simple cylinder (without any electrode) reported by Ref. [19] and a cylinder with electrodes on when the plasma actuator is off which was carried out by Ref. [14]. From Fig. 6, it is clear that the electrodes (both the wire and planar electrodes) are able to disturb the pressure distribution considerably. An important note that can be understood from the research conducted by Ref. [14] diagram is: approximately from 50° up to 110°, the wire electrode and from 130° up to 180°, the planar electrode deviated the results from what was reported by Ref. [19]. It means that the existence of the electrodes played an important role in changing the pressure coefficient distribution and also lift and drag coefficients of a circular cylinder in contrast to a simple cylinder. These effects should be analyzed and studied by detail.

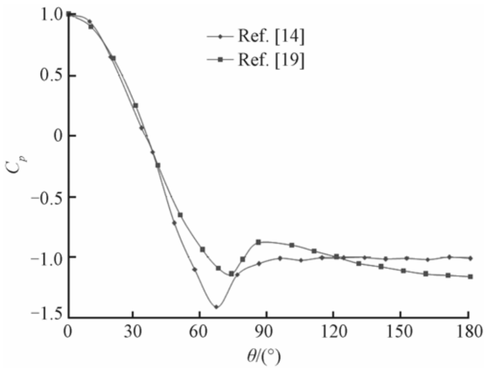

Fig. 6. Pressure coefficient comparison of a simple cylinder with a cylinder in the presence of electrodes.

In this section we are going to present our pressure coefficient distribution results for all configurations of plasma actuator in the conditions of plasma off at Re = 63 825 and compare the results with the pressure coefficient distribution of a simple cylinder reported by Ref. [20] in order to analyze the effect of electrodes on pressure distribution of the cylinder.

First we begin with our initial configuration (Configuration 1). Figure 7 shows the pressure coefficient distribution result for Configuration 1 and the comparison of this result with the pressure coefficient distribution of a simple cylinder carried out by Ref. [20].

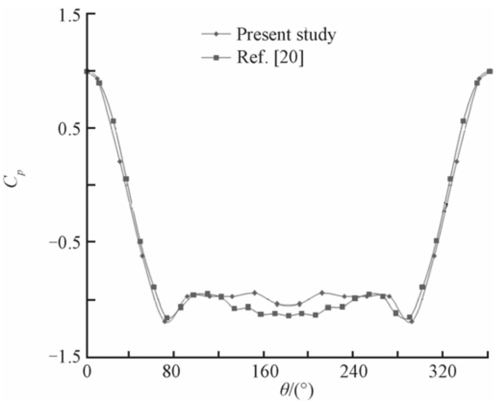

Fig. 7 Pressure coefficient distribution for Configuration 1.

Figure 7 shows that for Configuration 1, no significant change could be detected due to the presence of the wire electrode in the pressure coefficient distribution because according to Fig. 7, from 0° up to 70°, our results are approximately the same as that of Ref. [20]. In fact when the angle of wire electrode is 0° or when the wire electrode locates at stagnation point, the wire electrode plays no considerable role in changing the pressure distribution of the cylinder. As was mentioned in Section 2.2, opposed to the research of Ref. [14], the wire electrode was embedded in a slit. Figure 7 shows that inserting the wire electrode into the slit would cause no important change in the pressure distribution. Reference [14] did not embed the wire electrode into a slit and Fig. 1 shows that the wire electrode has changed the pressure coefficient distribution of the cylinder significantly especially from 50° up to 70°. The planar electrode has changed the pressure coefficient distribution of the cylinder for both our study and that of Ref. [14]. In our study, the planar electrode covers nearly from 130° up to 230° of the cylinder whereas for Ref. [14] this range was about 140° up to 222°. From Fig. 1 and Fig. 7, it is clear that the planar electrode has changed the pressure coefficient distribution of the cylinder for the range of angles that is related to the existence of the planar electrode.

Figure 8 shows the pressure coefficient distribution result for Configuration 2 and the comparison between our results with that of Ref. [20].

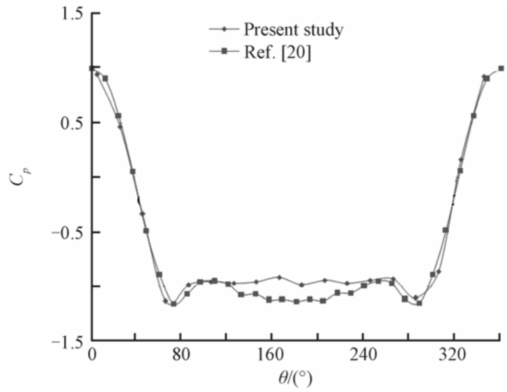

Fig. 8 Pressure coefficient distribution for Configuration 2.

Figure 8 shows that for Configuration 2, the wire electrode produces no significant change in the pressure coefficient distribution of the cylinder. The planar electrode in this configuration covers nearly 145° up to 244° of the cylinder and Fig. 8 shows that in this range of angles, the planar electrode has changed the pressure coefficient distribution considerably. So at this configuration, the effect of the planar electrode is more significant compared with the wire one.

Figure 9 shows the pressure coefficient distribution result for Configuration 3 and the comparison with that of Ref. [20].

In this configuration, both the wire and the planar electrodes have changed the pressure coefficient distribution. Figure 9 shows that the existence of the wire electrode has changed the pressure coefficient distribu-

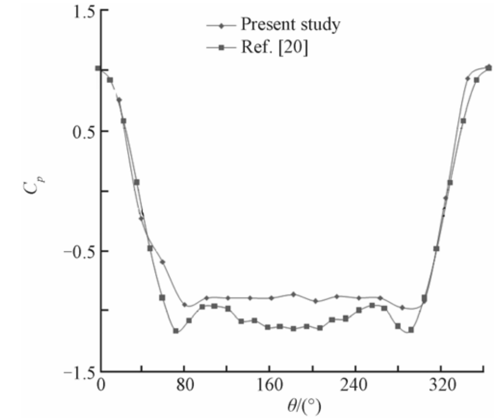

Fig. 9 Pressure coefficient distribution for Configuration 3.

tion from about 50° up to 160°. On the other hand, planar electrode covers approximately from 160° up to 260° of the cylinder. As is clear from Fig. 9, the planar electrode has changed the pressure coefficient distribution considerably especially from about 160° up to 280°. Therefore in this configuration, both electrodes have played an important role in changing the pressure distribution of the cylinder by comparing our result with that of Ref. [20].

Figure 10 shows the comparison between the pressure coefficient distribution of Configuration 4 and the pressure coefficient distribution of a simple cylinder reported by Ref. [20].

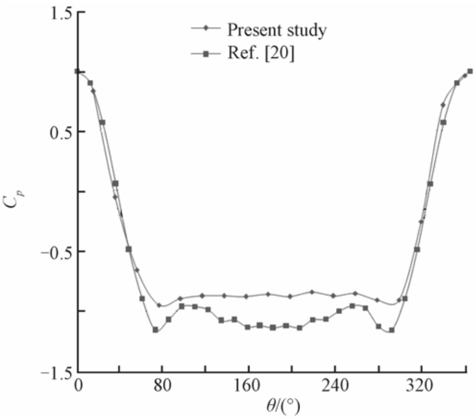

Fig. 10 Pressure coefficient distribution for Configuration 4.

In this configuration like the previous one (Configuration 3), both the wire and the planar electrodes have changed the pressure coefficient distribution of the cylinder. Figure 10 shows that the existence of the wire electrode has changed the pressure coefficient distribution from about 60° up to 175°. For this configuration, the planar electrode covers the cylinder approximately from 175° up to 275°. It is clear from Fig. 10 that the planar electrode has changed the pressure coefficient distribution of the cylinder especially at this range of angles (from 175° up to 275°). It is important to note that the effect of the planar electrode has spread up to 295° considerably. Therefore for this configuration, both electrodes are effective in changing the pressure coefficient distribution of the cylinder.

The effect of the wire electrode on the pressure coefficient distribution of the cylinder from about 70° up to 190° has been shown in Fig. 11. In this configuration, the planar electrode covers about 190° up to 290° of the cylinder and the effect of this electrode on the pressure coefficient distribution is considerably effective in this range. So for this configuration both electrodes are effective in changing the pressure coefficient distribution result.

Figure 12 shows the pressure coefficient distribution of the cylinder for Configuration 6 and the comparison of this result with that of Ref. [20]. The significant effect of the wire electrode on the pressure coefficient distribution of the cylinder has been shown from about 85° up to 205°. In this configuration, the planar electrode covers about 205° up to 305° of the cylinder and from Fig. 12 it is clear that the planar electrode has considerably changed the pressure coefficient distribution of the cylinder in this range of angles. Therefore in this configuration like the previous one, both electrodes are effective in changing the pressure coefficient distribution of the cylinder.

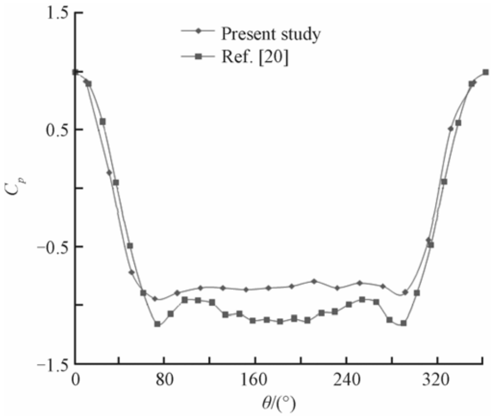

Fig. 11 Pressure coefficient distribution for Configuration 5.

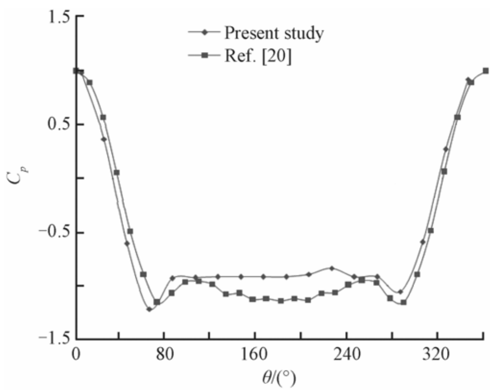

Fig. 12 Pressure coefficient distribution for Configuration 6.

Figure 13 shows the comparison between the pressure coefficient distributions of the cylinder for Configuration 7 with that of Ref. [20].

Figure 13 shows that the effect of the wire electrode on the pressure coefficient distribution of the cylinder is about from 130° up to 220°. In this configuration, the planar electrode covers nearly 220° up to 320° of the cylinder. According to Fig. 13, the planar electrode

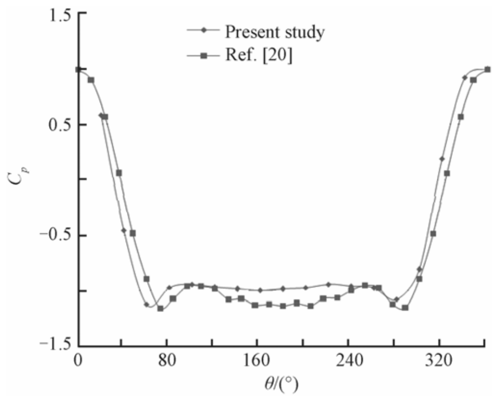

Fig. 13 Pressure coefficient distribution for Configuration 7.

has changed the pressure coefficient distribution of the cylinder especially from 220° up to 320°. It is important to mention that the effect of the planar electrode has also spread up to about 90°. So in this configuration the effect of the planar electrode on the pressure coefficient distribution of the cylinder is more than the wire one.

Figure 14 shows the pressure coefficient distribution of the cylinder for Configuration 8 and also the comparison between this result with that of Ref. [20].

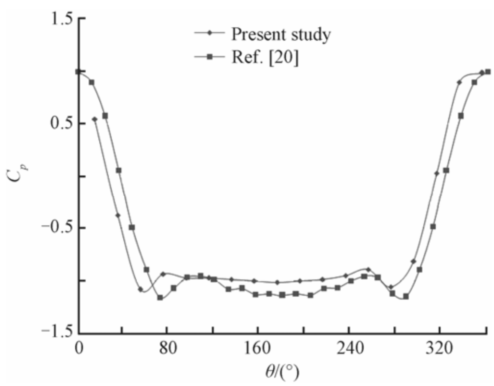

Fig. 14 Pressure coefficient distribution for Configuration 8.

The range of effect of wire electrode has been shown in Fig. 14 which is approximately from 125° up to 235°. In this configuration, the planar electrode covers nearly from 235° up to 335° of the cylinder. The range of effect of this electrode on the pressure coefficient distribution of the cylinder has been shown in Fig. 14 which is about 235° up to 335° and also spread up to about 85°. It is clear from Fig. 14 that the role of the planar electrode in this configuration is more effective in changing the pressure coefficient distribution of the cylinder than the wire one.

Figure 15 shows the pressure coefficient distribution for Configuration 9 and the comparison of this result with that of Ref. [20].

It is obvious from Fig. 15 that the range of effect of the wire electrode on the pressure coefficient distribution of the cylinder is almost from 130° up to 250°. The planar electrode covers about 250° up to 350° of the cylinder in this configuration. The range of effect of the planar electrode on the pressure coefficient distribution of the cylinder is almost from 250° up to 350°. In addition to this range, the effect of the planar electrode has even spread more up to about 90°. This phenomenon shows that for this configuration, the effect of the planar electrode is more in contrast to the wire one.

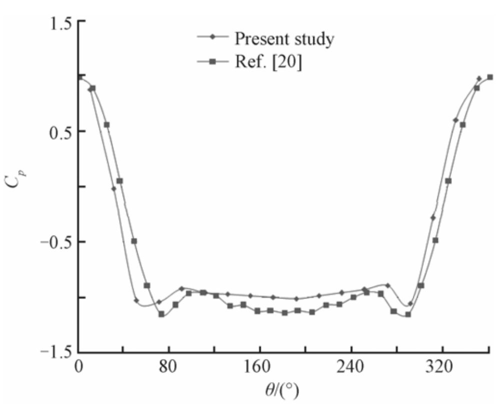

Fig. 15 Pressure coefficient distribution for Configuration 9.

Figure 16 shows the pressure coefficient distribution of the cylinder for Configuration 10 and the comparison of the result with that of Ref. [20].

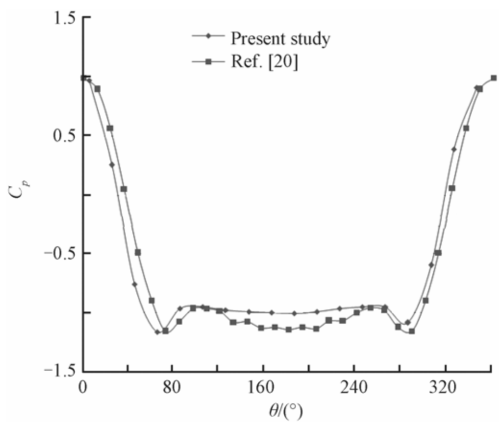

Fig. 16 Pressure coefficient distribution for Configuration 10.

The existence of the wire electrode has changed the pressure coefficient distribution of the cylinder. From Fig. 16 it is clear that the range of effect of the wire electrode on the pressure coefficient distribution is approximately from 145° up to 265°. The planar electrode in this configuration covers about 265° to 5° of the cylinder. From Fig. 16 we realize that in this configuration the effect of the planar electrode is more than the wire one and even the effect of the planar electrode has spread up to nearly 85°. Therefore for this configuration, the role of the planar electrode in changing the pressure coefficient distribution is more effective compared with the wire electrode.

Figure 17 shows the pressure coefficient distribution of the cylinder for Configuration 11 and the comparison with that of Ref. [20]. The effect of the wire electrode on the pressure coefficient distribution of the cylinder has been detected from about 160° up to 280°.

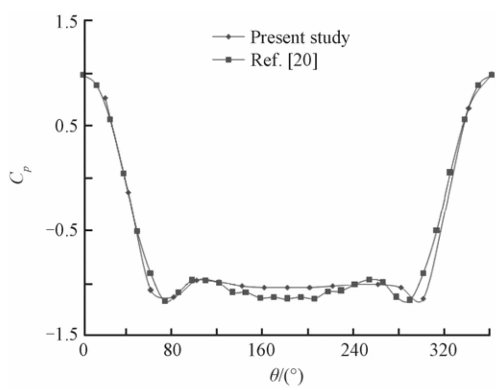

Fig. 17 Pressure coefficient distribution for Configuration 11.

In this configuration the planar electrode covers almost from 280° up to 20° of the cylinder but as it can be seen in Fig. 17, the effect of the planar electrode on the pressure coefficient distribution of the cylinder is negligible in contrast to the effect of the wire electrode. The range of effect of the planar electrode on the pressure distribution is approximately from 280° up to 320°. So it is clear that in this configuration the effect of the wire electrode is more than the effect of the planar one.

Figure 18 shows the pressure coefficient distribution of the cylinder for Configuration 12 and the comparison of our result with that of Ref. [20].

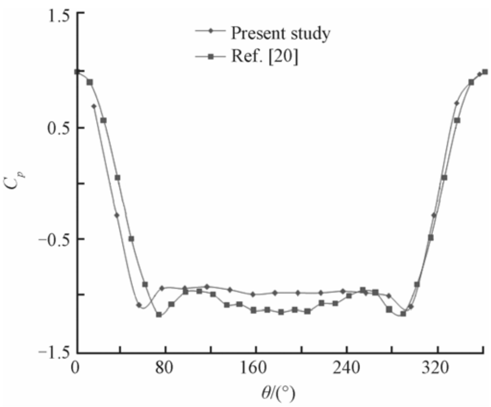

Fig. 18 Pressure coefficient distribution for Configuration 12.

In this configuration, both the wire and the planar electrodes have changed the pressure coefficient distribution as well. The existence of the wire electrode has changed the pressure coefficient distribution approximately from 175° up to 295°. On the other hand, the planar electrode in this configuration covers nearly from 295° up to 35° of the cylinder. The range of effect of the planar electrode is about 295° up to 35° which has been even spread up to 155° considerably. Therefore both electrodes are effective in this configuration.

Figure 19 shows the pressure coefficient distribution of the cylinder for Configuration 13 and the comparison between this result with that of Ref. [20]. The effect of the wire electrode on the pressure coefficient distribution of the cylinder is considerable and the

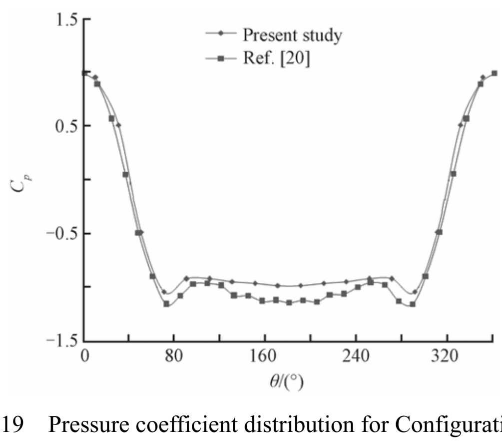

Fig. 19 Pressure coefficient distribution for Configuration 13.

range of effect of the wire electrode is nearly from 190° up to 290°. The planar electrode covers almost from 310° up to 50° of the cylinder in this configuration. As it is clear from Fig. 19, the effect of the planar electrode is not that sensible, so for this configuration, the wire electrode has played an important role in changing the pressure coefficient distribution of the cylinder.

In this section the effects of the wire and the planar electrodes on the pressure coefficient distribution of the cylinder in plasma off state at Re = 63 825 were investigated experimentally. The results were compared with the pressure coefficient distribution of a simple cylinder (with no electrodes on) which was carried out by Ref. [20]. It was concluded that the existence of both electrodes can change the pressure coefficient distribution of the cylinder and produce disturbance in the flow field around the cylinder and change the behavior of the drag coefficient C_D of the circular cylinder significantly. Figure 20 shows the behavior of the drag coefficient of our study and the drag coefficient of Ref. [20]. As is clear, both electrodes have played an important role in changing the flow structure around the cylinder. This phenomenon will make the drag coefficient of our study become significantly different in comparison with that of Ref. [20]. The drag coefficient of the cylinder in this range of Reynolds number is approximately 1.2 (Ref. [20]) but from Fig. 20 it will be realized that the existence of the slit and also the electrodes or any extra objects on the cylinder, is capable of changing the value of the drag coefficient as well and should be considered carefully.

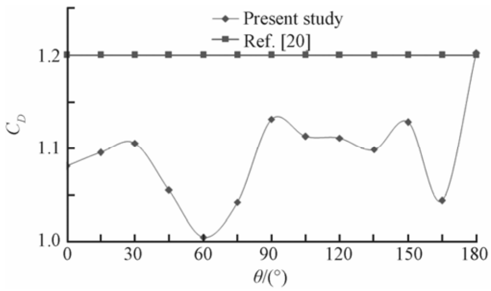

Fig. 20 Drag coefficient distribution.

3.3. *Effect of the plasma on pressure coefficient distribution of the cylinder*

In this section, we are going to present the effect of the plasma on the pressure coefficient distribution of the cylinder at Re = 63 825 for all configurations of the plasma actuator. In other words, the main aim of this section is to compare the pressure coefficient distribution of the cylinder in plasma off and plasma on conditions. It is important to note that all the experiments in plasma on condition for all configurations of plasma actuators have been carried out in generalized glow regime which was discussed completely in Section 3.1.

Figure 21 shows the pressure coefficient distribution of the cylinder for Configuration 1 in plasma off and plasma on conditions.

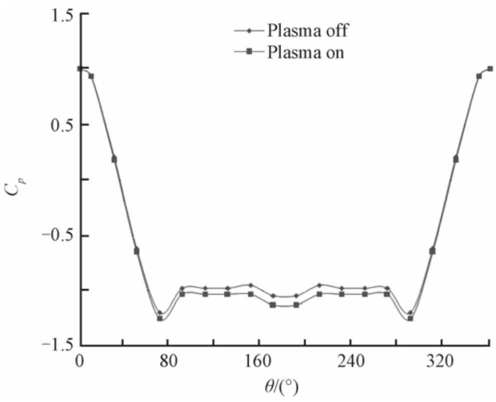

Fig. 21 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 1.

From Fig. 21, it is clear that when the plasma actuator becomes active, no significant change could be observed before the separation point. As soon as the flow separates (about 80° and 280°), the momentum of the ionized flow (plasma) would change the structure of the near-wake behind the cylinder and thus makes it larger in comparison with plasma off condition. The relative pressure of the near-wake region is lower than the relative pressure of the free stream. This will cause more suction at the downstream of the cylinder. This phenomenon makes the pressure coefficient of the cylinder lower with plasma on. It is important to note that for Configuration 1, the pressure coefficient distribution of the cylinder is symmetric and the plasma plays no important role in changing the separation point.

Figure 22 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 2.

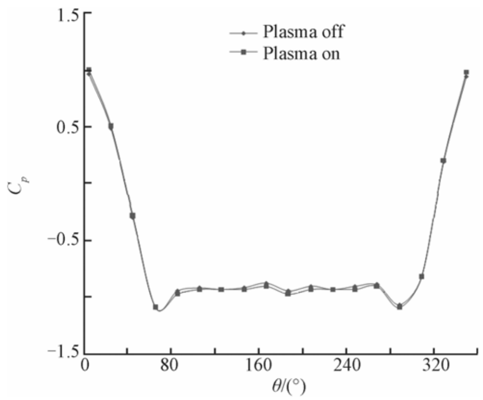

Fig. 22 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 2.

Figure 22 represents that for Configuration 2, before the separation point, there is no significant change in the pressure coefficient distribution of the cylinder. As explained for Configuration 1, after the separation point, the suction at the downstream of the cylinder would decrease the pressure coefficient coefficient especially from 165° up to 205°. In this configuration, flow separation occurs at about 85° and 265° in both plasma off and on conditions.

Figure 23 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 3. It is obvious from Fig. 23 that the activation of plasma actuator would significantly decrease the pressure coefficient coefficient after the separation point because of the suction appearing at the downstream of the cylinder similar to previous configurations. In this configuration, the flow separates approximately at 80° and 280° in both plasma off and on conditions.

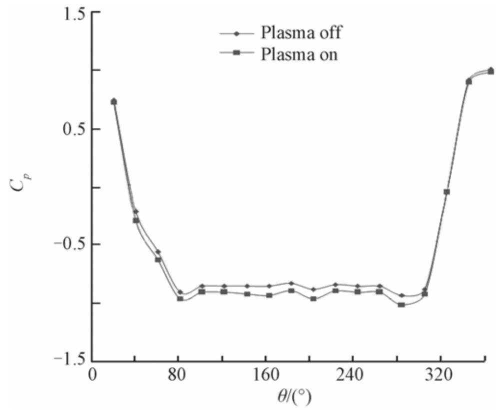

Fig. 23 Effect of the plasma on the pressure coefficient distribution of the cylinder for Configuration 3.

Although the reduction of the pressure coefficient occurs after the separation point but before the separation point, as the plasma actuator activates, the existence of the wire electrode causes the pressure coefficient of the cylinder to decrease considerably from 40° up to 60°.

Figure 24 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 4. It is clear from Fig. 24 that after separation, the existence of the plasma decreases the pressure coefficient of the cylinder significantly due to the fact that suction occurs at downstream of the cylinder similar to Configuration 3 (see Fig. 23). In this configuration, the flow separates at 75° and 275° in

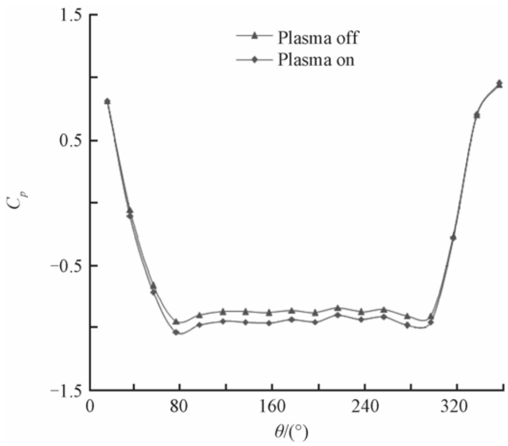

Fig. 24 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 4.

both plasma off and on conditions. So the plasma plays no important role in changing the separation points for this configuration.

Figure 25 describes the pressure coefficient coefficient of the cylinder in both plasma off and on conditions for Configuration 5.

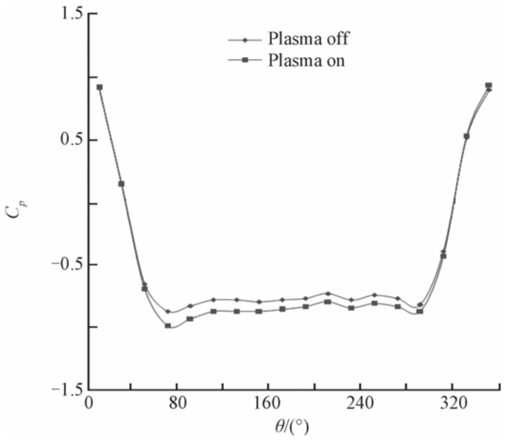

Fig. 25 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 5.

Figure 25 shows that as the plasma actuator activates, after the separation point, the momentum of the ionized flow (plasma) forces the near-wake to develop more at the downstream of the cylinder and suction will occur. This phenomenon would decrease the pressure coefficient coefficient of the cylinder significantly especially after the separation point. It is important to say that when the plasma actuator becomes active, the existence of the plasma has changed the pressure coefficient distribution of the cylinder and has decreased the pressure coefficient coefficient of the cylinder from 70° up to about 290°. In this configuration, the separation points in both plasma off and on conditions occur at the same point.

In Fig. 26, the results of the pressure coefficient distribution of the cylinder in both plasma off and on conditions have been presented for Configuration 6.

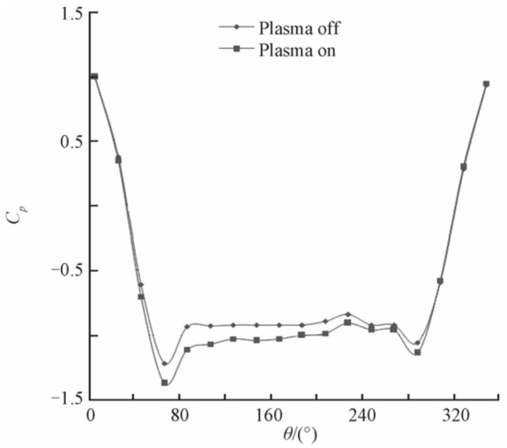

Fig. 26 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 6.

Figure 26 shows that the reduction of the pressure coefficient of the cylinder for Configuration 6 is more significant compared to Configuration 5 because in Configuration 6, the distance between the wire electrode and the separation point is less than that of Configuration 5. In other words in Configuration 6, the distance between the wire electrode and the separation point is minimum in contrast to the previous configurations. Therefore in this state, the near-wake will encounter the maximum momentum of the ionized flow (plasma) so that the separated boundary layer would develop to the downstream of the cylinder more than Configuration 5. This will cause more suction for Configuration 6 and consequently more reduction in the pressure coefficient in comparison with Configuration 5. In Configuration 6, plasma has not changed the separation point (the separation region is approximately at 85° and 265°).

Figure 27 shows the pressure coefficient distribution of the cylinder in plasma off and plasma on conditions for Configuration 7.

In this configuration, the wire electrode locates at the near-wake region and Fig. 27 shows no significant change on the pressure coefficient distribution of the cylinder due to the existence of the plasma because no momentum can be exerted on the near-wake region and there would be no significant suction at the downstream of the cylinder. For Configuration 7, the flow separates approximately at 80° and 260° in both plasma off and on conditions.

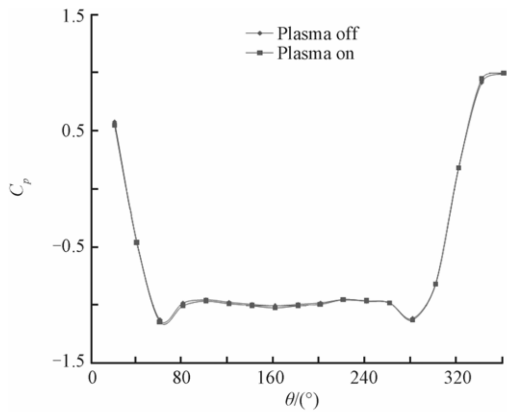

Fig. 27 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 7.

Figure 28 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 8.

In this configuration similar to the previous one, the wire electrode locates at the near-wake region and consequently no significant change could be detected due to the existence of the plasma either on the pressure coefficient distribution of the cylinder or on the separation point. It is necessary to mention that in this configuration, the flow separates at about 75° and 255° in both plasma off and on conditions.

Figure 29 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 9.

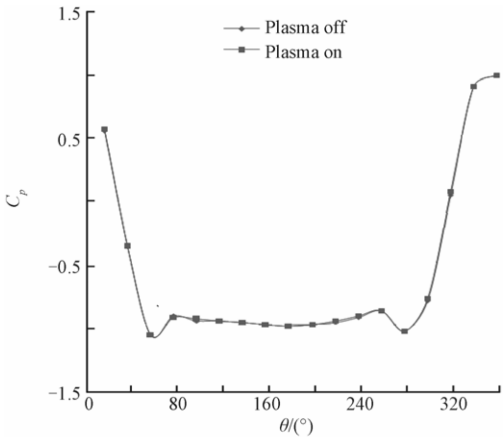

Fig. 28 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 8.

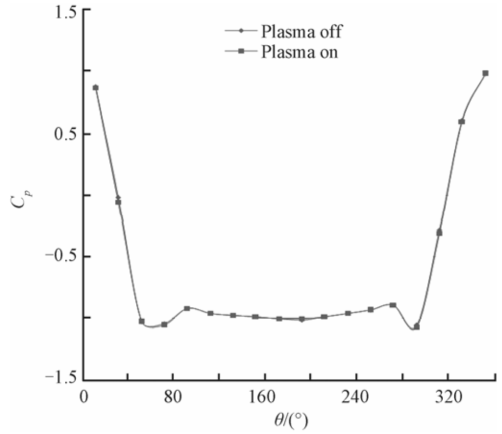

Fig. 29 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 9.

The wire electrode in this configuration like Configurations 7 and 8, locates at the near-wake region. So according to Fig. 29 no considerable change could be detected due to the existence of the plasma either on the pressure coefficient distribution of the cylinder or on the separation point. The separation point for this configuration is approximately at 80° and 270° in both plasma off and on conditions.

Figure 30 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 10.

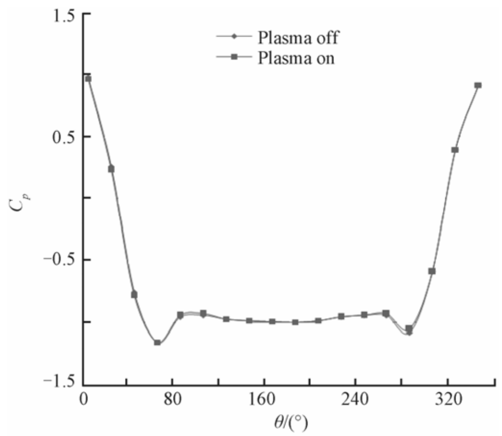

Fig. 30 Effect of the plasma on the pressure coefficient distribution of the cylinder for Configuration 10.

Similar to Configurations 7, 8 and 9, for this configuration, the wire electrode locates at the near-wake region and it is obvious from Fig. 30 that there is no considerable effect either on the pressure coefficient coefficient of the cylinder or on the separation point. In this configuration, the separation occurs at 85° and 265° in both plasma off and on conditions.

Figure 31 shows the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 11.

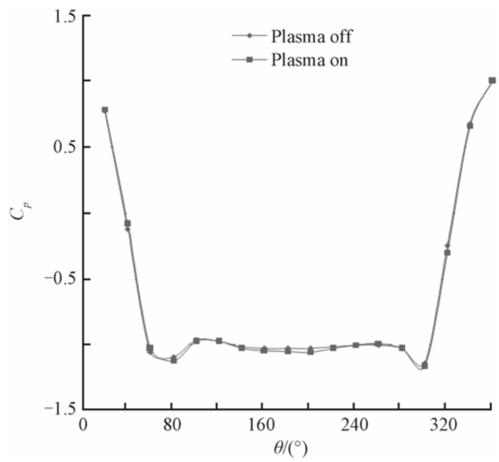

Fig. 31 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 11.

The wire electrode in this configuration, similar to Configurations 7, 8, 9 and 10, locates at the near-wake region. So according to Fig. 31, no important change could be detected on both the pressure coefficient distribution of the cylinder and the separation point. In Configuration 10, the flow separates approximately at 90° and 280° for plasma off and plasma on conditions.

In Fig. 32, the results of the pressure coefficient distribution of the cylinder in both plasma off and on conditions for Configuration 12 have been presented. The wire electrode in this configuration similar to Configurations 7, 8, 9, 10 and 11, locates at the near-wake region. As it is clear, from Fig. 32, no considerable

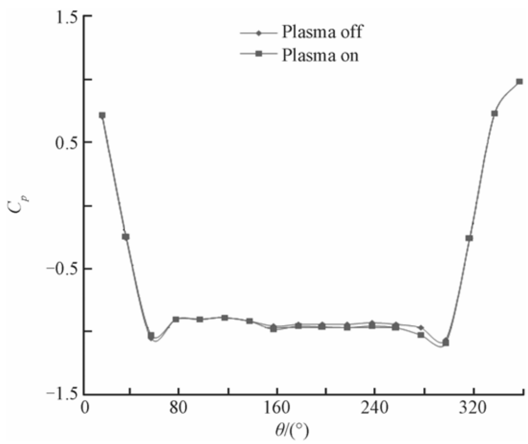

Fig. 32 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 12.

change could be detected both on the pressure coefficient distribution of the cylinder and also on the separation point. According to Fig. 32, the flow separation occurs approximately at 75° and 275° the plasma actuator being either off or on.

Figure 33 shows the pressure coefficient distribution of the cylinder for Configuration 13 in both plasma off and on conditions.

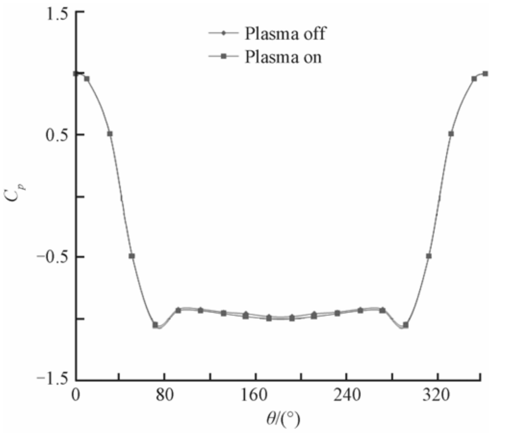

Fig. 33 Effect of the plasma on pressure coefficient distribution of the cylinder for Configuration 13.

In this configuration like Configurations 7, 8, 9, 10, 11 and 12, the wire electrode locates at the near-wake region. As it is clear from Fig. 33, the plasma has played no important role both on the pressure distribution of the cylinder and also on the separation point. In this configuration, the flow separates approximately at 80° and 280° for the plasma actuator being either off or on. So in this configuration, the plasma is useless in changing or delaying the separation point.

In this section the effect of the plasma on the pressure coefficient distribution of the cylinder for all configurations were investigated. The results showed that for Configurations 1 to 6, as the plasma actuator activates, the existence of the plasma decreases the pressure coefficient of the cylinder after the separation points. The reasons of the reduction of the pressure coefficient are as follows:

1) As the flow separates, the momentum of the plasma forces the separated boundary layer to develop more to the downstream of the cylinder. This phenomenon will cause the near-wake region to become larger. The static pressure of the near-wake region is less than the ambient pressure so that the near-wake region becomes larger, the difference between the static pressure of this region with the ambient pressure increases and this causes more suction to occur. That is why for Configurations 1 to 6, the existence of the plasma decreases the pressure coefficient of the cylinder.

2) Since the pressure coefficient distribution of the cylinder is changed due to the plasma actuator, the velocity distribution is changed as well. Therefore the shear stress is changed. It means that as the near-wake region becomes larger, the shear stress increases and this phenomenon is also effective in reduction of pressure coefficient of the cylinder. This phenomenon was also reported by Ref. [14].

Opposed to Configurations 1 to 6, for Configurations 7 to 13, the wire electrode locates at the near-wake region, so no momentum of the plasma will encounter with the separated boundary layer. Therefore no significant changes could be observed for pressure coefficient of the cylinder for these configurations.

3.4. Effect of the plasma on lift and drag coefficients of the cylinder

The lift coefficient C_L and drag coefficient C_D of the cylinder for each configuration were calculated according to the pressure coefficient distribution of the cylinder. Figure 34 shows the behavior of the drag coefficient of the cylinder for all configurations of the plasma actuator in both plasma off and on conditions.

It is clear from Fig. 34 that from 0° up to 75°, the effect of the plasma on the drag coefficient of the cylinder is significantly considerable. It is important to emphasize that at both 60° and 75°, the existence of the plasma has increased the drag coefficient because as it was mentioned before, for these two configurations, the distance between the wire electrode and the separation point is less than those of the other configurations and more momentum will be exerted on the separated boundary layer so that it would develop more at the downstream of the cylinder. This will cause more suction at the downstream of the cylinder so the drag coefficient will be increased. According to Fig. 34, from 90° up to 180°, the plasma has played no significant role in variation of the drag coefficient of the cylinder in contrast to 0° up to 75° because at this range of angles, the wire electrode locates at the near-wake region and no important momentum can be exerted on the separated boundary layer. According to these results, it is concluded that the plasma can be effective on the drag coefficient of the cylinder if the wire electrode is positioned out of the near-wake region.

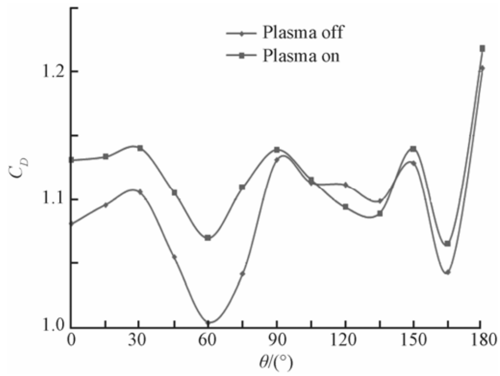

Fig. 34 Drag coefficient of the cylinder for all configurations of plasma actuator in both plasma off and on conditions.

Figure 35 shows the behavior of the lift coefficient of the cylinder in both plasma off and on conditions for all configurations of plasma actuator. As stated previously, the pressure coefficient distribution of the cylinder for Configurations 1 and 13 is symmetric. So the lift coefficient of the cylinder for these two configurations is zero.

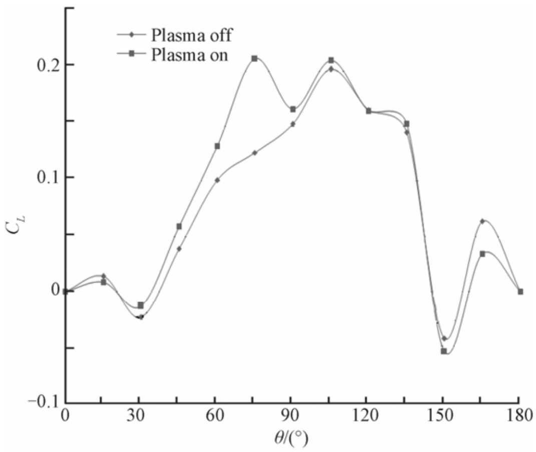

Fig. 35 Lift coefficient of the cylinder for all configurations of plasma actuator in both plasma off and on conditions.

For the other configurations due to the asymmetry in the flow field, we have lift for both plasma off and on conditions and the most effective configuration is Configuration 6 because in Configuration 6, the distance between the wire electrode and the separation point is minimum compared with the other configurations. This would cause the separated region to expose with the maximum momentum of the ionized air (plasma) and develop more at the downstream of the cylinder. This phenomenon increases suction at the downstream of the cylinder and makes the pressure coefficient of the upper surface less than that of the lower one. So the plasma would increase the lift coefficient considerably for Configuration 6. For the other configurations (Configurations 7 to 13), the effect of the plasma on the lift coefficient is not that sensible.

Figure 36 shows the aerodynamic performance parameter (C_L/C_D) versus the angular position of the wire electrode. The existence of the plasma increases significantly the values of the lift and drag coefficients of the cylinder, so the ratio of the lift coefficient to the drag coefficient is maximum for Configuration 6.

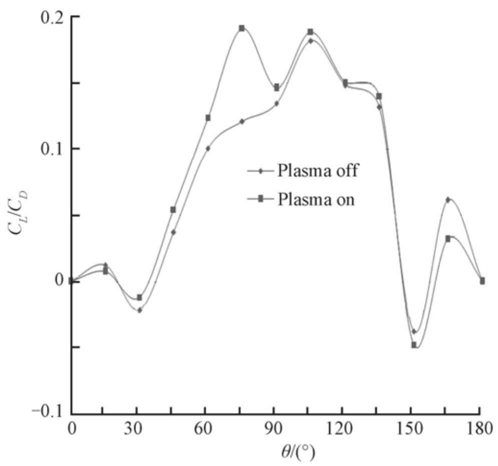

Fig. 36 C_L/C_D ratio for all configurations of plasma actuator in both plasma off and on conditions.

It is concluded that for Configuration 6 or better to say when the angle of the wire electrode is 75°, the aerodynamic performance of the cylinder is the best in comparison with the other configurations.

4. Conclusions

In this study we experimentally investigated the effects of the electrodes and also different configurations of plasma actuator on the flow structure around a circular cylinder which is made of PVC. For this goal, two electrodes are flush-mounted on the surface of the cylinder and are connected to a DC high voltage power supply in order to produce electrical discharge. The electrodes consist of a wire electrode and a planar one which are located at θ = 0° and θ = 180° respectively as the initial configuration. Many configurations of plasma actuator are studied by rotating the cylinder in clockwise direction at various angles. The first pressure coefficient distribution results show that at Re = 63 825 (u = 37 m/s), the existence of the electrodes on the cylinder in plasma off conditions can change the pressure coefficient distribution of the cylinder and also the lift and drag coefficients. We compare our first results with the pressure coefficient distribution of a simple cylinder. The second pressure distribution results are performed at Re = 63 825 for all configurations in both plasma off and on conditions. The results of this part show that the existence of the plasma can decrease the pressure coefficient of the cylinder significantly for Configurations 1 to 6. The reduction of the pressure coefficient produces suction at the downstream of the cylinder and this will increase the drag coefficient of the cylinder for these configurations. For Configurations 5 and 6, the plasma has the most influence in comparison with the other configurations because the distance between the wire electrode and the separation point is less among the others. From Configuration 7 to 13, the wire electrode locates at the near-wake region and no considerable change could be detected on the drag coefficient of the cylinder. For lift coefficient from Configurations 7 to 13 no important change could be reported due to the existence of the plasma but for Configuration 6, the plasma has increased the lift coefficient of the cylinder considerably in contrast to the other configurations, because in this configuration the distance between the wire electrode and the separation point is minimum and the separated region would develop more at the downstream of the cylinder due to the existence of the maximum momentum of the ionized fluid (plasma). More suction at the downstream of the cylinder will cause more reduction in the pressure coefficient of the upper surface in comparison with the lower one. Therefore the lift coefficient is maximum for Configuration 6. The most suitable configuration having the best aerodynamic performance refers to the configuration with the most C_L/C_D parameter. For Configuration 6, both the lift and drag coefficients of the cylinder have become larger due to the existence of the plasma. So for this configuration, the parameter C_L/C_D is maximum.

As we explained in this paper, the existence of the electrodes on the cylinder has changed the pressure coefficient distribution of the cylinder. The wire electrode of our study embedded in a slit whereas the planar electrode located in front of the wire electrode. We concluded that the existence of both the wire and planar electrodes or any extra object on the cylinder is able to change the pressure distribution of the cylinder and also the behavior of the lift and drag coefficients as well.

Generally in order to decrease the effects of the electrodes (when using a wire and a planar electrode) on the pressure coefficient distribution of the cylinder, we recommend using a planar electrode (aluminum foil) instead of the wire one. The width of this planar electrode should be reduced carefully until the width of it reaches approximately 1 mm. Therefore for such condition, this planar electrode can play the role of a wire electrode as well with less effect on the pressure coefficient distribution of the cylinder.

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Biography:

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